A Conceptual Geologic Model for the Newberry Volcano EGS Site in Central Oregon: Constraining Heat Capacity and Permeability through Interpretation of Multicomponent Geosystems Data

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ABSTRACT

Newberry Volcano, a voluminous (500 km^3) basaltic/andesitic/rhyolitic shield volcano located near the intersection of the Cascade volcanic arc, the Oregon High Lava Plains and Brothers Fault Zone, and the northern Basin and Range Province, has been the site of geothermal exploration for more than 40 years. This has resulted in a unique resource: an extensive set of surficial and subsurface information appropriate to constrain the baseline structure of, and conditions within a high heat capacity magmatically hosted geothermal system.

In 2012 and 2014 AltaRock Energy conducted repeated stimulation of an enhanced geothermal systems (EGS) prospect along the western flank of the Newberry Volcano. A surface based monitoring effort was conducted independent of these stimulation attempts in both 2012 and 2014 through a collaboration between NETL, Oregon State University and Zonge International. This program included utilization of 3-D and 4-D magnetotelluric, InSAR, ground-based interferometric radar, and microgravity observations within and surrounding the planned EGS stimulation zone. These observations as well as borehole and microseismic stress field and location solutions provided by AltaRock and its collaborators, in combination with well logs, petrologic and geochemical data sets, LIDAR mapping of fault traces and extrusive volcanics, surficial geologic mapping and seismic tomography, have resulted in development of a framework, subsurface geologic model for Newberry Volcano.

The Newberry subsurface geologic model is a three-dimensional digital model constructed in EarthVision™ that enables lithology, directly and remotely measured material properties, and derived properties such as permeability, porosity and temperature, to be co-registered. This provides a powerful tool for characterizing and evaluating the sustainability of the site for EGS production and testing, particularly within the data-dense western portion of the volcano. The model has implications for understanding the previous EGS stimulations at Newberry as well as supporting future research and resource characterization opportunities. A portion of the Newberry area has been selected as a candidate site for the DOE FORGE (Frontier Observatory for Research in Geothermal Energy) Program through a collaboration between Pacific Northwest National Laboratory, Oregon State University, AltaRock Energy and additional partners. Thus, the conceptual geologic model presented here will support and benefit from future enhancements associated with that effort.

1. INTRODUCTION

The enhanced geothermal system (EGS) potential in the western United States of 200,000 exajoules (EJ) represents nearly 2,000 times the United States' 2013 annual energy consumption of 102.5 EJ (Annual Energy Outlook, 2016). Suitability evaluations of geologic systems and conditions are paramount to harnessing this massive resource, where advancements in EGS technologies may develop and exploit these assets. Newberry Volcano is one such geologic system of interest; its resident high thermal potential, petrology, tectonic setting and proximity to consumer markets provide an ideal candidate for the advancement of geothermal energy in the volcanically active western United States. Newberry volcano combines the features of magmatism characteristic of the Cascades volcanic arc and other "Ring-of-Fire" subduction zone related volcanic systems, with Basin-and-Range influenced volcanism that extends eastward into the continental interior. Newberry Volcano also hosts diverse material types, including granitic as well as basaltic/andesitic/rhyolitic formations at depth, which are found within the low fluid permeability, elevated temperature conditions that have been specified for EGS development by the US Department of Energy. This range of geologic conditions provide EGS test conditions that can represent those found in other areas throughout the western US.

Newberry Volcano is located east of the main trend of the High Cascades volcanic arc in the U.S. state of Oregon. The volcano is in proximity to critical energy infrastructure, including a Bonneville Power Administration high voltage transmission line located 10 km to the west of the volcano's west flank. This volcanic system hosts current geothermal activity within its caldera. Newberry's west flank, the location of recent EGS exploration carried out by AltaRock Energy Inc., lies outside the National Monument protection boundary and hosts subsurface temperatures and depth ranges within the EGS target of 175°C-225°C and 1.4-4.0 km, respectively. Subsurface permeabilities in this target are below the level that typically supports natural hydrothermal circulation. Downhole equilibrium temperatures at depths greater than 3 km beneath parts of the west flank has been directly measured as high as ~325°C, providing a

future pathway to economic commercial development of this resource. Newberry's lithology presents a wide range of volcanic products that provide abundant dry rock, the prime host to hydrofracture- and hydroshear-induced permeability necessary for EGS. To further understand and utilize this system, we recognized a need for a baseline geologic model that captures both what is known about the system and gaps in knowledge that can be analyzed in future research.

Decades-long interest in Newberry, both geologically and as a geothermal prospect has led to a uniquely characterized system. Here, we combine multiple historical datasets evaluating the Newberry subsurface with recent research and development efforts undertaken by Oregon State University (OSU), AltaRock Energy Inc., Davenport-Newberry Holdings, National Energy Technology Laboratory (NETL) and Zonge International to inform a conceptual geologic model that combines a multitude of data types. These datasets constrain key parameters involved in EGS system evaluation: temperature profiles, porosity, permeability, stress regime, structure, lithology, petrology, and fluid content that influence the extent and suitability of target reservoir rock units for EGS development and production. In addition to providing constraint on key parameters, the conceptual geologic model allows for the user to compare and contrast future datasets that allow for the reduction of subsurface uncertainty.

2. BACKGROUND

Located 50 km east of the Cascade axis in the state of Oregon, Newberry Volcano is an active shield volcano that lies above the Juan de Fuca/Gorda plate subduction zone at the intersection of the Brothers Fault Zone, the High Lava Plains, and the northern Basin and Range province. It is the largest of Oregon's volcanoes at 32 kilometers in diameter and a volume approximately 20 times that of Mount Saint Helens, another Cascade volcano that lies off of the main axis of the Cascades volcanic arc. The volcano's caldera has existed for at least 500,000 years after forming from an eruption that discharged an estimated 42 cubic kilometers of volcanic product. There have been six eruptions since the late Pleistocene, with the most recent significant eruptive episode occurring approximately 1,310 years before present (Sherrod, et al., 1997).
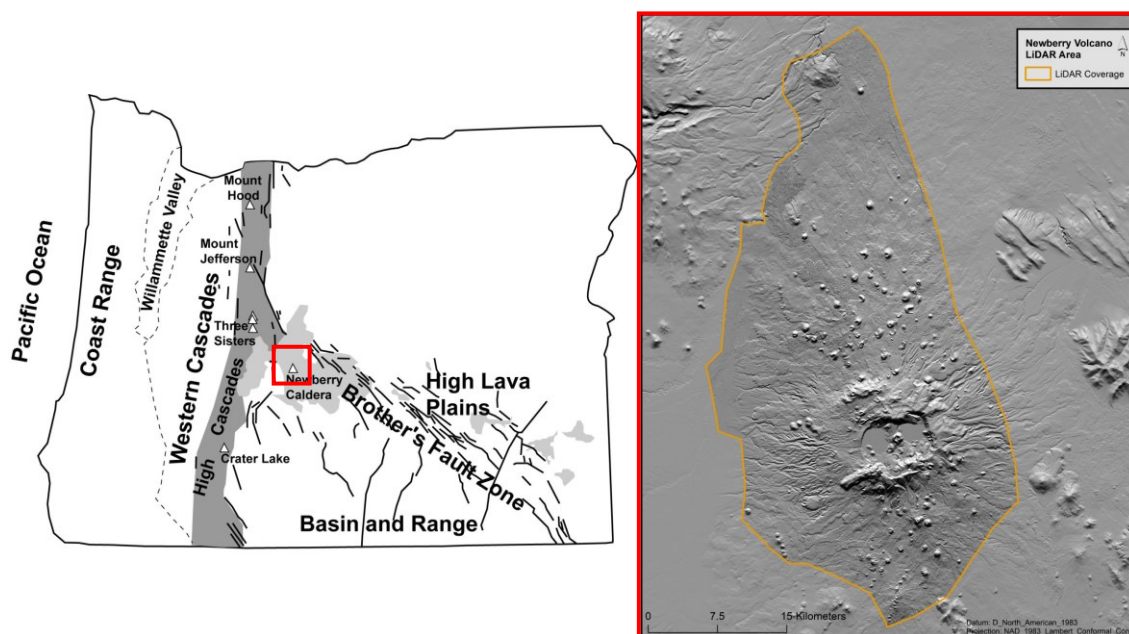

Figure 1: (left) Regional map showing location of Newberry Volcano. High Cascades are shown in dark gray and High Lava Plains are shown in light gray (Schmidt and Grunder, 2009). (right) Sub-1m LiDAR map of Newberry Volcano, located in Central Oregon (DOGAMI, 2010).

Despite being situated east of the main trend of the volcanic arc, Newberry is generally considered to be a Cascades volcano based on the similarities of its magma chemistry, which groups closely with those typical of nearby Cascades volcanoes, while the Basin and Range extensional tectonics likely influence its eruptive history (Catchings and Mooney, 1988, Donnelly-Nolan et al., 2008). The intersection of the Brothers, Sisters, and Walker Rim fault zones influence the stress regimes of Newberry Volcano. Cinder cone and fissure vent deposits trending N-S lie parallel to the latter two aforementioned fault zones. Newberry eruptions have been bimodal, including the range of silicic to mafic volcanics. For further information on eruptive products and geomorphology, see the companion paper by Bonneville et al. (2016). The presence of a molten magma chamber may explain the contrasting eruption compositions; research to constrain its presence beneath the Newberry Caldera has found fractional change in seismic velocity that potentially confirms this hypothesis (Fitterman, 1988, Heath, 2015). Observed high temperatures on the west flank (Sammel et al., 1988, Frone et al., 2014), imply an alternate, more spatially extensive heat source to explain high temperatures on the flank (Frone et al., 2014).

The west flank of Newberry Volcano has been of interest to geothermal development due to abundant evidence for extensive intrusive volcanics beneath the volcano edifice. At depths of approximately 3 kilometers, a region of high seismic velocity, high density and high temperatures occur (Achauer et al., 1988, Catchings and Mooney, 1988, Gettings and Griscom, 1988, Waibel et al., 2014). At greater depths (>3 kilometers) seismic and magnetotelluric studies have inferred a large intrusive complex beneath the volcano edifice (Stauber

et al., 1988, Catchings and Mooney, 1988, Fitterman et al., 1988). This large intrusive complex may contribute to the overall high thermal temperatures on the volcano (Sammel et al. 1988, Frone et al., 2014). Ongoing analysis of more recently acquired wideband magnetotelluric and microgravity data obtained by the authors during 2012 and 2014 is also illuminating finer-scale features beneath the west flank, which is helping to establish preferred EGS target areas.

2.1 Suitability as an EGS site

The combination of high temperatures, high total eruptive and intrusive volume, recent eruptive activity and ease of access relative to other Cascades Range volcanoes make Newberry a prime EGS (Enhanced Geothermal System) target (Urquhart, 1988, JGR special issue: Newberry Volcano, 1988). Previous studies recording high temperatures on the west flank did not find large-scale circulation of fluids in the subsurface (Waibel et al., 2014). Anomalously high temperature data on the west flank of the volcano can be explained by silicic sill intrusions recurring at a rate of 200,000 years over the 500,000 year lifetime of Newberry Volcano (Frone et al., 2014). There are no other active volcanoes in the United States that provide such high quality, deep temperature and thermal conductivity constraints (Blackwell, 1994, Spielman and Finger, 1998). Risk of groundwater contamination via site development and operation are low due to an impermeable zone of enhanced clay content that separates shallow groundwater in the upper 300 meters of the subsurface on the west flank. An established EGS system at Newberry Volcano would be in close proximity to necessary energy infrastructure and is capable of providing power to population centers such as the city of Bend in Deschutes County and beyond.

3. BASELINE GEOLOGIC MODEL OF NEWBERRY VOLCANO

In 2012 and 2014, AltaRock Energy, Inc. in collaboration with Davenport Newberry Holdings LLC began and then successfully achieved stimulation of an existing hot well using hydroshearing and multi-zone isolation techniques in effort to create an EGS reservoir. An independent project designed to monitor this simulation was conducted using surface based geophysical techniques. The effort used advanced geophysical capabilities including portable radar interferometry, high-resolution satellite InSAR, 3-D and 4-D magnetotelluric imaging methods, and high-resolution gravimetry in combination with geologic and geochemical information about the subsurface system. In order to compare and contrast future monitoring datasets with the wealth of existing research in the Newberry vicinity, a baseline geologic model and geospatial interpretation of the subsurface system of Newberry Volcano has been developed, and continues to evolve.

For this model, we used EarthVision™ 3-D model building software from Dynamic Graphics, Inc. Developed for subsurface modeling in exploration and production scenarios, EarthVision™ allows for input and integration of multiple layers, datasets and geologic features from a variety of geophysical, geological, and exploration methods. This software is capable of representing key parameters to an EGS system that vary across layers e.g. heat capacity, porosity, permeability, and stress. EarthVision™ is also able to create cross-sections and isolation of layers, intrusions, and data that allow for targeting sites of interest.
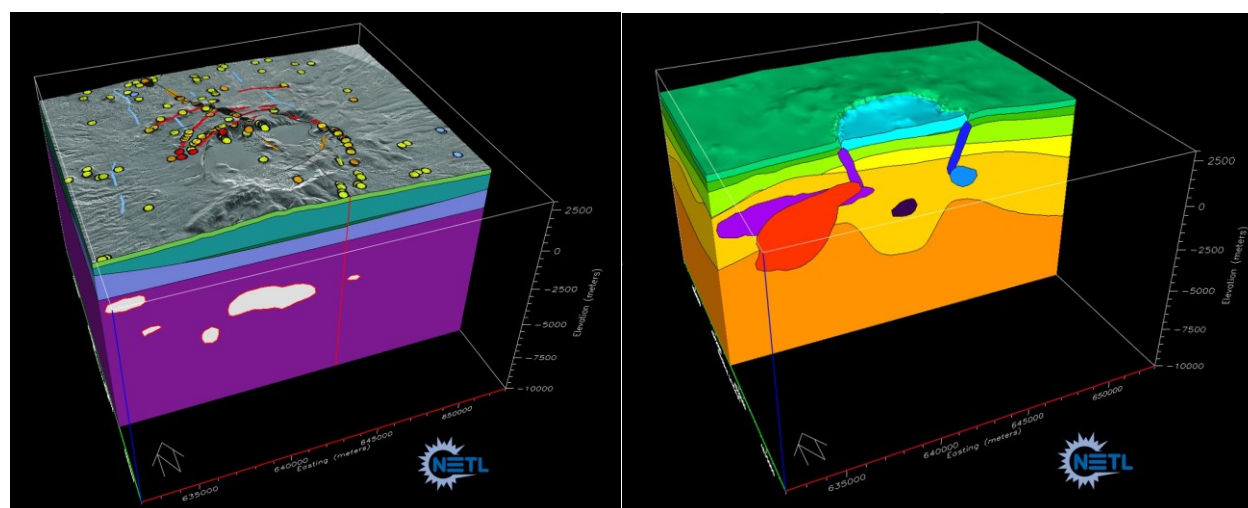

Figure 2: Representative 3D displays of the Newberry geologic and geophysical models created in EarthVision™. In the geologic model (left), subsurface layers are largely adapted from Sonnenthal (2012), posited intrusive bodies are in white, and fault boundaries appear as red lines. Grasso et al.'s (2012) map of volcanic vents, fissures, and faults is draped over the surface topography. In the geophysical model (right), geophysical layers representing conductive and resistive layers constrained from electrical data are represented along with the tomographically constrained intrusive bodies shown in blue, purple, and red. Note that the cross-sections are not taken in the same location.

Data and dataset availability is greatest at the western flank of Newberry Volcano as this area is the focus of EGS development. A paucity of datasets in other areas, due to National Monument restrictions and lack of interest in development, mean much of the structure of the volcano has yet to be surveyed. In order to create the most accurate model possible in areas of less data density, such as the deep John Day formation, we relied on EarthVision's interpolation algorithms and the use of reasonably approximated data from scientific literature to constrain the geological horizon in a way that was amenable to these algorithms. The remedial use of approximated data solves unpredictable interpolation issues in addition to improved constraint of modeling parameters.

3.1 Datasets

The following datasets represent the range and variety of methods used to characterize the subsurface and geothermal potential of Newberry Volcano. Many are publicly available via the United States Geological Survey (USGS), Pacific Northwest Seismic Network (PNSN), Oregon Department of Geology and Mineral Industries (DOGAMI), and the Journal of Geophysical Research Special Issue 1988 on Newberry Volcano, while others have been acquired by the authors under DOE support and have been curated and will be made available for distribution through the Department of Energy EDX and GDR nodes of the National Geothermal Data System (NGDS).

3.1.1 Topography

Topography is constrained by a 200 meter by 200 meter grid defined from the model in Beachly et al. (2012). Improved resolution topography from LiDAR/DEM data will also be incorporated into this model using data from the Oregon Department of Geology and Mineral Industries (DOGAMI, 2010).

3.1.2 Geologic observation

Many decades of accumulated geologic observation and inferred knowledge are available for the Newberry EGS site. Early comprehensive observation from Williams (1938) laid the foundation for the geologic maps produced for the USGS by MacLeod et al. (1995) and Grasso et al. (2012), both of which are used in this model as topographical overlays to inform surficial geologic features and subsurface interpretation. Structural interpretations from surface observations include caldera faulting from Fitterman et al. (1988), MacLeod et al. (1995), and Grasso et al. (2012). Subsurface layers draw from geologic cross-sections by MacLeod et al. (1995), and Sonnenthal (2012).

3.1.3 Well data

Wellbore based datasets support both geologic and geophysical interpretations in this model. Both publicly available and proprietary well data were used to inform the model. DOGAMI's GTILO databaseprovides well information including date of drilling, lithology, and wellbore temperature readings (DOGAMI, 2016). In addition to supporting thermal contours, well data provide ground-truthing to the lithologic interpretation in the model.

3.1.4 Gravity

A variety of gravity resources are utilized in this model. Low-resolution gravity data obtained from the USGS Publications Warehouse serves as a property input. For higher resolution, gravity data conducted by Davenport and Zonge International allow for more detailed modeling. Data from Zonge International analyzed by (Waibel et al., 2014) reveals a gravity high on the west flank of the volcano that has been interpreted as a granite intrusion. This intrusion is depth constrained by well logs from west flank locations that indicate the presence of granite at certain depths; however, the location of the gravity high is poorly constrained and is considered to be an approximate placeholder for future gravity inversions. Zonge International's 2012 microgravity inversion density model, seen below in Figure 3, shows high-density bodies that may also be interpreted as granitic intrusions (Zonge International, 2012). A comprehensive 3-D inversion of the complete merged gravity dataset is currently underway for NEWGEN efforts, outlined in the companion paper by Bonneville et al. (2016).

3.1.5 Electrical results

Electrical results from a variety of studies support the geophysical aspect of the model. The depth to the top surface of an electrically conductive zone based on magnetotelluric (MT) data as interpreted by Waibel et al. (2014) is coarsely discretized, with points predominately on the west flank. Fitterman et al. (1988) present a depth to top of a conductive zone based on transient electromagnetic (TEM) data and an electrical basement based on MT data. It should be noted that the Fitterman et al. (1988) MT does not match the MT conductor depth found in Waibel et al. (2014). Recent long-period and wideband MT data from Schultz et al. collected in 2011, 2012 and 2014 is currently being inverted for a higher-resolution 3-D view of electrical properties, and will be implemented in the EarthVision™ model (Schultz, 2014).

3.1.6 Seismic tomography

Seismic tomography reveals a number of potential intrusive bodies in the Newberry subsurface according to data from Achauer et al. (1988), and Heath et al. (2015), with several large bodies imaged beneath the west flank. Heath et al., (2015) constrain a magma chamber between 3 and 5 km depth. Volumes for the model intrusions are based on fractional change in seismic velocity.
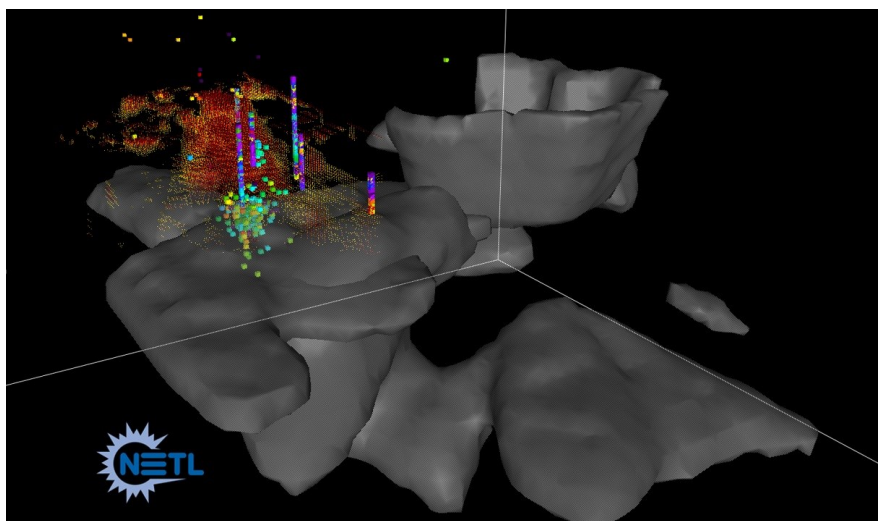
Figure 3: A representative 3D display of the Newberry intrusive bodies (transparent gray), focused and zoomed to the west flank. Multicolor pillars represent wells 23-22, 46-16, 55-29, 86-21, N-2, and N-5; well 55-29 intersects with the inferred granitic intrusive body at approximately 1200 m depth. Multicolor boxes represent microseismic event data collected by the Pacific Northwest Seismic Network. Transparent red bodies represent microgravity data collected from Zonge International, which is rendered to show density values greater than 2.8 g/cm^3 (approximate density of granite). 3.1.7 Seismic monitoring

Deep long period (DLP) and microseismic earthquake data obtained from Pacific Northwest Seismic Network is seen as a model input in figure 3 (PNSN, 2015). DLPs are indicative of magma movement beneath both the caldera and the southwest flank of Newberry Volcano, however the accuracy of event locations is impacted by uncertainties in the seismic velocity structure .
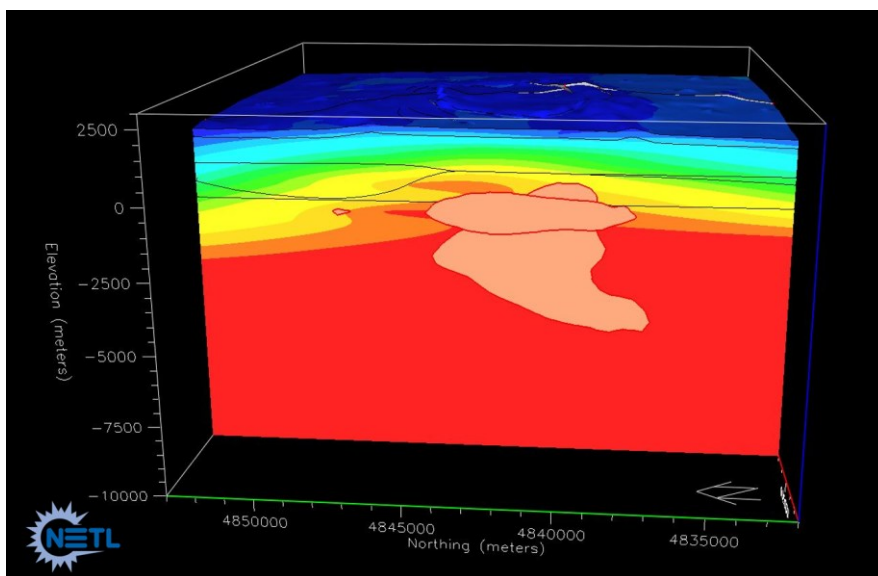
3.2 Results

Figure 4: 3-D display of the current Newberry temperature model created in EarthVision™. The image displays a cross-section through the west flank looking eastward; temperature ranges from -18°C [0 °F] (blue) above ground surface temperature to 315°C [600 °F] above ground surface temperature (red). Note the west flank intrusive bodies are constrained by tomography (peach); black lines indicate geologic layer boundaries. The temperature model will improve with forthcoming data, constrained by inferred magma chamber partial melt fraction and the regional geotherm, and by probabilistic uncertainty analysis.

Our EarthVision™ model is currently separated into two domains; a 3-D model of observed geophysical parameters, and a 3-D model of geological features, each of which can be loaded into EarthVision™'s viewer for side-by-side comparison. This function is critical to the progression of the model for reducing uncertainty of the volcano's subsurface, and for understanding data and interpretation from the multiple methods listed in the previous subsection. The western portion of the model has the best data resolution given the high interest in geothermal development on the west flank, with wellbore-scale interpretations supporting subsurface modeling in this area. The resolution and data constraints weaken eastward as less exploration and development have been pursued in this region, therefore

much of the model in this area relies on EarthVision™'s layer interpolation. Property modeling options within our modeling software has allowed for thermal contouring and input of hydrogeological information from Sonnenthal et al. (2015) for geologic layers; property inputs for porosity and permeability are forthcoming that will further reduce informational gaps and subsurface uncertainty. The model figures presented in this paper should be considered representative, as the model is continuously evolving as data are collected, interpreted, and properly constrained.

4. CONCLUSIONS

The realization of the full potential of an EGS play depends on certain key factors, including knowledge of the temporal-spatial variation in temperature, crack volume, fluid chemistry and the presence of mineralization products within the rock matrix, all of which can impact hydraulic conductivity through their effects on porosity and permeability. The profusion of data collected for Newberry Volcano supports the knowledge necessary for many of these parameters but at varying scales and resolutions across the region. The Newberry subsurface geologic model has allowed for the integration of public and key proprietary data. This resource supports future gap analyses, identification of areas where there may be greater uncertainty and thus need for future data collection, visualization opportunities to support advanced interpretations and assessments of the subsurface system, and offers a framework upon which geophysical, geochemical and other datasets can be modeled, validated, and evaluated against the current state of knowledge. This baseline conceptual geologic model will continue to grow and evolve as new data, models, and insights about the subsurface system at Newberry continue to emerge. In support of that the Newberry geologic model will be made discoverable and accessible once it is appropriate for release, through DOE's public data management systems, EERE's OpenEI.org and NETL's EDX.

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